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POTENTIAL ELECTRON BEAM INDUCED FLASHBLINDNESS IN  
PILOTS(U) TEXAS A AND M RESEARCH FOUNDATION COLLEGE  
STATION N D MILLER ET AL. NOV 86 USAFSAM-TR-86-31  
F33615-83-D-0602

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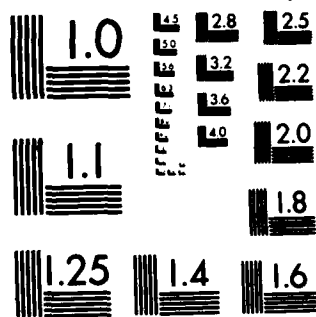
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REPORT DOCUMENTATION PAGE				
1a. REPORT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>		1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE				
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S) USAFSAM-TR-86-31		
6a. NAME OF PERFORMING ORGANIZATION Texas A&M Research Foundation Texas A&M University	6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION USAF School of Aerospace Medicine (RZV)		
6c. ADDRESS (City, State, and ZIP Code) College Station, Texas 77843-3572		7b. ADDRESS (City, State, and ZIP Code) Aerospace Medical Division (AFSC) Brooks Air Force Base, TX 78235-5301		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F33615-83-D-0602-0020		
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS		
		PROGRAM ELEMENT NO. 62202F	PROJECT NO. 7757	TASK NO. 05
		WORK UNIT ACCESSION NO. 64		
11. TITLE (Include Security Classification)  POTENTIAL ELECTRON BEAM INDUCED FLASHBLINDNESS IN PILOTS				
12. PERSONAL AUTHOR(S) Miller, Norma, and Wheeler, Thomas G.				
13a. TYPE OF REPORT Final Report	13b. TIME COVERED FROM Oct 1985 TO Aug 1986	14. DATE OF REPORT (Year, Month, Day) 1986 November	15. PAGE COUNT 27	
16. SUPPLEMENTARY NOTATION				
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	Cerenkov radiation; flashblindness in pilots; and electron beam related to flashblindness.	
06	21			
06	18			
19. ABSTRACT (Continue on reverse if necessary and identify by block number)  A simplified but representative situation of a flat windscreen and visor in front of a pilot's eyes has been defined to evaluate the potential for flashblindness caused by Cerenkov radiation, produced by a 1-sec exposure to relativistic electrons with velocities of about 0.95 c. The beam density corresponding to 1 rad is $10^7$ e <sup>-</sup> /cm <sup>2</sup> . (The Cerenkov radiation produced in the eye by 6 MeV (0.996 c) electrons was compared to light from external sources in a previous study.) The spectral and spatial distribution of the Cerenkov radiation in the windscreen and visor from the electron beam has been calculated to find the additional retinal illumination contributed by them. $\rightarrow$ DTE  The total Cerenkov radiation produced in the windscreen and visor is approximately $3 \times 10^3$ times greater than that in the eye; but the amount of radiation which enters the pupils is only 2% of that produced in the eyes for a mid-scotopic range of $5 \times 10^{-4}$ cd/m <sup>2</sup> ,  (Cont'd. on p.ii)				
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Thomas G. Wheeler, Ph.D			22b. TELEPHONE (Include Area Code) (512) 536-3684	22c. OFFICE SYMBOL USAFSAM/RZV

## 19. ABSTRACT (Cont'd.)

and only 0.3% for a mid-photopic range of 100 cd/m<sup>2</sup>. The Cerenkov radiation from the windscreen and visor is concentrated in arcs of a narrow ring at a visual angle of 67.4° around the fovea. For scotopic vision, the arcs are overlaid on the Cerenkov light in the eye. Because of the Stiles-Crawford effect, the only visually effective Cerenkov light produced in the eye for cones lies in a ring around the fovea, and the external Cerenkov light from the transparencies does not coincide with the photons produced within the eye.

On the basis of the calculations performed and of a brief survey of existing data, the following five estimates (a-e) can be made:

- a. Absolute threshold for the Cerenkov <sup>microrad</sup> radiation from the windscreen and that produced in the eye is equivalent to a 3 ~~urad~~ beam of 0.95 c electrons.
- b. Cone threshold for the Cerenkov radiation produced in the eye is equivalent to 0.8 rads; and, for that produced in the windscreen, 0.09 rad
- c. Extrapolating from foveal and parafoveal data, a 10-rad beam would cause a 2.5-sec interruption in visibility for low contrast targets in the mid-scotopic adaptation range in the region of the image of the windscreen arcs.
- d. Insufficient data exist for proper evaluation of the flashblindness effect in the periphery at scotopic levels, so the estimate in item c may be conservative by a large factor.
- e. No possibility exists for flashblindness from Cerenkov radiation in the mid-photopic range at sublethal doses.

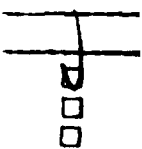
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## POTENTIAL ELECTRON BEAM INDUCED FLASHBLINDNESS IN PILOTS

### INTRODUCTION

Cerenkov radiation is visible light that is produced when charged particles, accelerated to relativistic velocities, traverse a transparent dielectric. While the total energy lost in passing through a dielectric (such as water, glass, or plastic) is a small fraction of the kinetic energy of the particle, the light is visually effective due to the eye's efficiency as a detector. Accelerators are capable of producing large beams of electrons with energies of several mega electron volts (MeV). Miller and Wheeler have already investigated the quantity of Cerenkov radiation produced in the eye by 6 MeV electrons (1). For such a beam, a density of  $2.3 \times 10^7 \text{ e}^-/\text{cm}^2$  has been found to equal 1 rad. The light formed in the eye by such a beam is equivalent to a retinal illumination of 4.6 scotopic troland (td)·sec (rod vision) or 0.55 photopic td·sec (cone vision). In practical terms, snow or very white sand in mid-dusk is of the order of 4 to 5 td.

Comparing the absolute threshold of the eye for external light and for Cerenkov radiation from accelerated electrons is of interest. If the eyes are completely dark adapted for at least an hour, they reach maximum sensitivity for light. Numerous studies have determined the minimum quantity of light necessary to elicit a visual response. For rod vision in the extra-foveal retina, the absolute threshold depends only on the number of quanta entering the eye for fields of  $1^\circ$  diam or less, and for exposure times of less than 1 sec (2-4). The average threshold reported is approximately 120 quanta of 507 nm light. One electron of 6 MeV passing through the eye produces, on the average, 170 equivalent quanta of 507 (1). These quanta would be spread over an area several thousand times larger than the image of a  $1^\circ$  field, however, due to the conical distribution of the Cerenkov radiation. For large fields and exposures of several seconds, the absolute threshold depends on the luminance of the field and is equivalent to a retinal illuminance of about  $2 \times 10^{-1}$  td. This value corresponds to 4  $\mu\text{rad}$  of 6 MeV electrons delivered in short bursts over 1 sec, as compared with a 0.5 mrad X-ray beam.

Flashblindness occurs when the eyes are subjected to the flash of light several orders of magnitude greater than the ambient illumination. A visual task comfortably above threshold detection before the flash will fall below threshold for a variable period after the flash. The duration of the flashblindness may be from a few seconds to many minutes, depending on the intensity and duration of the flash. The major

amount of the work in flashblindness has been concerned with massive light exposures, of the order of the electromagnetic pulse from nuclear detonations, and with the effect on photopic vision. Such exposures could only occur from Cerenkov radiation from lethal doses of accelerated particles.

The present study was undertaken to consider not only the additional light produced in the windscreen and visor of a pilot subjected to an accelerated beam, but also the effect on the pilot's vision.

### SPECTRAL DISTRIBUTION AND INTENSITY OF CERENKOV RADIATION

For the purpose of this report, a simplified but representative situation has been defined. The windscreen is a 3-cm thick plate of plastic with an index of refraction of 1.4, and the visor is a 2-mm sheet of the same index. Both transparencies are flat and are, respectively, 26 cm and 3 cm from the pilot's eyes. The electron beam is uniformly distributed over the surface and perpendicular to it. The velocity in relation to the speed of light ( $c$ ) of the electrons is about 0.95  $c$  (energy equal to 2 MeV). A dose of 1 rad is equivalent to a beam density of  $10^7 e^-/cm^2$ , and the beam duration is less than 1 sec. (The configuration of the windscreen, visor, and eyes is shown in Fig. 1.)

Frank and Tamm (5) derived an equation for the quantity of Cerenkov radiation from a particle passing through a dielectric of index of refraction  $n$ . The equation yields the number of quanta per centimeter of path length in a band of frequencies,  $\Delta\nu$

$$N = (2\pi ze)^2 \Delta\nu \cdot \sin^2 \theta / hc^2 \quad (1)$$

where  $ze$  is the charge on the particle,  $c$  is the velocity of light in a vacuum, and  $h$  is Planck's constant. The radiation is confined to a cone of half-angle  $\theta$ , given by

$$\cos \theta = 1/\beta n \quad (2)$$

where  $\beta$  equals the ratio of the particle velocity to that of light in a vacuum. Equation 1 is useful for photopigment absorption, because the absorption curves refer to an equal quanta spectrum. A more useful quantity for visual effects is the energy per uniform wavelength intervals per second. The standard relative luminosity values for transforming radiant power to photometric units are based on an equal energy spectrum. Multiplying the number of quanta by the energy per quantum ( $Q_e$ ), and transforming the frequency intervals to constant wavelength intervals, Eq. 1 becomes:

$$Q_e = (2\pi ze)^2 \sin^2 \theta \Delta\lambda / \lambda^3 \quad (3)$$

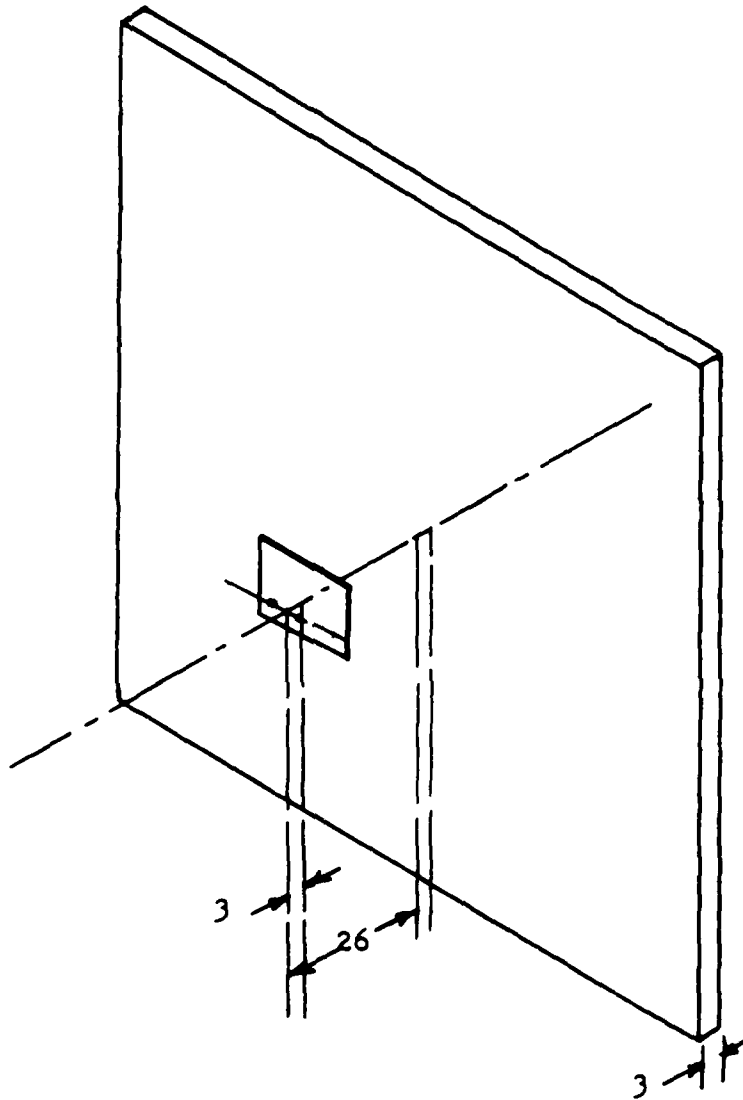


Figure 1. The distances between the windscreen and the eyes, and the visor and the eyes. All distances are in centimeters.

The charge on the electron is  $-4.8 \times 10^{-10}$  electrostatic units (esu). Thus, the radiant flux per centimeter of path length per  $e^-$  per 10-nm wavelength interval is:

$$Q_e = 9.1 \times 10^{-19} \sin^2 \theta / \lambda^3 \text{ Joules,} \quad (4)$$

where  $\lambda$  is the central wavelength of the spectral band and is expressed in micrometers ( $\mu\text{m}$ ).

The quantities calculated from Eq. 4 must be converted to luminous flux to find the visual effect of the radiation. Inspection of the equation reveals that the spectral distribution is independent of the electron velocity or the index of refraction of the medium, but depends only on the inverse third power of the wavelength. The quantity of the radiation, on the other hand, is dependent on the velocity and index through the  $\sin^2 \theta$  factor, thus permitting a general solution for the photometric conversions. The relative luminosity factors,  $V_\lambda$  for cone vision and  $V'_\lambda$  for rod vision, can be multiplied by  $1/\lambda^3$  and summed to find the relative amount of 555 nm light for  $V_\lambda$  and of 507 nm light for  $V'_\lambda$ . One watt of 555 nm light is equal to 680 photopic lumens (lm), and one watt of 507 nm equals 1750 scotopic lumens, based on the definition of the standard candle. The luminous energy from each electron per centimeter of path length is:

$$Q_v = 3.89 \times 10^{-14} \sin^2 \theta \text{ photopic lm}\cdot\text{s, and} \quad (5)$$

$$Q_v = 1.26 \times 10^{-13} \sin^2 \theta \text{ scotopic lm}\cdot\text{s.}$$

From Eq. 2, for our representative case with 0.95 c electrons, the value for  $\theta$  for the windscreen and visor is  $41.25^\circ$ , thus giving

$$\sin^2 \theta = 0.4347 .$$

By use of the experimentally determined value of

$$1 \text{ rad} = 10^7 e^-/\text{cm}^2 \text{ for } 0.95 \text{ c,}$$

the total luminous energy produced in the windscreen and visor can be found from Eqs. 5 and 6. These values are listed, in Table 1, with the values for the eye.

TABLE 1. TOTAL VISUALLY EFFECTIVE CERENKOV RADIATION PRODUCED BY 1 RAD OF 0.95 c ELECTRONS DELIVERED IN 1 SEC IN LUMEN·SEC

<u>Medium</u>	<u>Vol (cm<sup>3</sup>)</u>	<u>Photopic</u>	<u>Scotopic</u>
Windscreen	$3 \times 10^4$	$5.1 \times 10^{-3}$	$1.7 \times 10^{-2}$
Visor	30.0	$5.1 \times 10^{-5}$	$1.7 \times 10^{-4}$
Eye	7.6	$1.4 \times 10^{-6}$	$6.0 \times 10^{-6}$

For the eye calculations, the relative luminosity factors must be corrected by the transmittance factors of the preretinal media. The lens absorbs almost all light below 380 nm, so practically no light from external sources below this wavelength can enter the eye to evoke a visual response. Rhodopsin, the rod pigment, is still an effective transducer of light down to 300 nm, as has been shown by people who have had their lenses removed for cataract. The eye calculations have, therefore, been performed with sensitivity data based on rhodopsin absorption curves and on electroretinography data on lensless subjects. Results were reported in the previous study (1), and have been corrected for the difference in energy of the electrons considered. The 2 MeV electrons assumed in this report have a reduction of 0.87 in the value of  $\sin^2 \theta$  and a factor of 2.3 in the beam density as compared with the 6-MeV of the previous study.

The retinal illumination corresponding to 1 rad of 2-MeV electrons can be found from the relationship:

$$1 \text{ td} = 10^{-6} \text{ lm/steradian of visual angle.} \quad (6)$$

A steradian (sr) of visual angle is 1.8 times that of the globe, because the visual angle is measured from the nodal point which is 16.8 mm from the retina. Therefore, for a beam duration of 1 sec,

$$1 \text{ rad} = 1.7 \text{ scotopic td}\cdot\text{sec.} \quad (7)$$

For large fields, the luminance at absolute threshold remains constant for durations greater than 100 msec(6), and the product of luminance and duration remains constant for shorter times. Thus, absolute threshold would be equivalent to a dose of 1  $\mu$ rad delivered in 100 msec or less.

Comparing the effectiveness of Cerenkov radiation produced in the eye with light from external sources for the cones is more difficult. This difficulty is due to the highly directional characteristics of the cones, known as the Stiles-Crawford effect. Light entering the eye near the edge of the dilated pupil is only 20% as effective as light entering the center of the pupil. The light from the edge of the pupil enters the cone at an angle of about  $11^\circ$  to its axis. The Cerenkov radiation in the eye will strike the retina over a wide range of angles relative to the receptor axes. (This problem is considered in the next section.)

The color of the light generated by the accelerated electrons is very blue, approximating that of a clear blue sky. The blue of the sky results from Rayleigh scattering, which has an inverse fourth power of the wavelength relationship as compared with the inverse third power of the Cerenkov radiation. The chromaticity coordinates are  $x = 0.26$  and  $y = 0.26$ , corresponding to a full body radiator locus at about  $22,000^\circ \text{ K}$ .

## SPATIAL DISTRIBUTION OF CERENKOV RADIATION

While the total luminous energy produced in the windscreen and visor is more than a thousand times greater than that produced in the eye, only the portion which enters the pupil of the eye is visually effective. The light from any electron striking the front surface of the windscreen will be contained in a cone of half angle  $41.25^\circ$ , with a base of 2.63-cm radius. The light will be refracted at the rear surface to emerge in an annulus. The angle of emergence,  $\theta'$ , measured from the normal, is given by Snell's Law:

$$\sin \theta' = n \sin \theta \quad . \quad (8)$$

The value of  $\theta'$  is  $67.38^\circ$  for our representative case.

The linear dimensions are shown in Figure 2, which depicts a horizontal plane through the pilot's eyes perpendicular to the windscreen. A plane passing through the pilot's entrance pupils and parallel to the windscreen will be called the illumination plane. A single electron passing through the windscreen would form an annulus of light on the illumination plane with an outside radius of 65 cm, and a width of 2.63 cm. The area of the annulus is  $1.05 \times 10^3 \text{ cm}^2$ ; therefore, the luminous energy ( $E_w$ ) at the illumination plane from one  $e^-$  is:

$$E_w = 1.56 \times 10^{-16} \text{ scotopic lm}\cdot\text{sec}/\text{cm}^2, \text{ and} \quad (9)$$

$$E_w = 4.83 \times 10^{-17} \text{ photopic lm}\cdot\text{sec}/\text{cm}^2 \quad (10)$$

The radius of the base of the cone of light in the visor is 0.175 cm, and the outer radius of the annulus is 7.37 cm. Therefore, the area of the annulus is  $8 \text{ cm}^2$  and the luminous energy per  $e^-$  at the illumination plane is:

$$E_v = 1.37 \times 10^{-13} \text{ scotopic lm}\cdot\text{sec}/\text{cm}^2, \text{ and} \quad (11)$$

$$E_v = 4.24 \times 10^{-14} \text{ photopic lm}\cdot\text{sec}/\text{cm}^2. \quad (12)$$

Shown in Figure 3 is a horizontal plane, through the pilot's eyes and perpendicular to the windscreen, with the extreme electrons and a central one. The diagram shows that none of the light emanating from electrons along the line of intersection of the horizontal plane and the windscreen enters the pilot's eyes. To find the area of the windscreen that produces light at the eyes, we can take the origin of a coordinate system at the center of the entrance pupil of one of the eyes. The z axis is perpendicular to the windscreen, and the x, y axes are parallel to it. All rays of light emerging from the rear surface will make an angle of  $67.38^\circ$  to the normals, which are parallel to the z axis. Shown in Figure 4 is a plane through the z axis at  $45^\circ$  to the x and y axes. The drawing makes obvious the fact that a line of electrons, 2.63 cm long (on the front surface of the windscreen), all contribute some light to a line 1 cm long on the illumination plane.

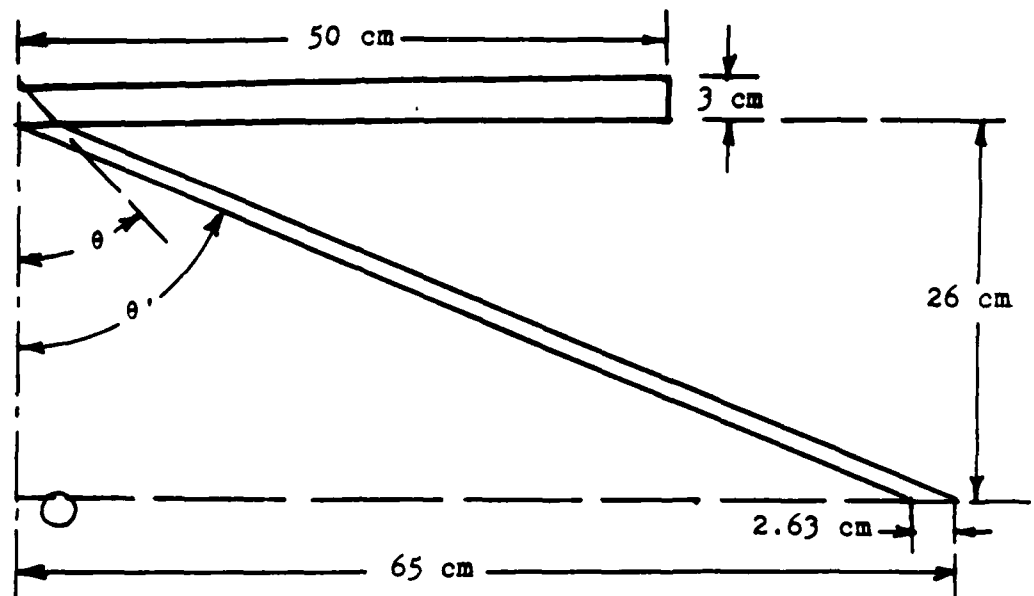


Figure 2. Linear dimensions of the windscreen and the path of light from an electron striking the center are shown on a horizontal plane through the pilot's eyes. The angle  $\theta$  is  $41.25^\circ$ , and  $\theta'$  is  $67.4^\circ$ .

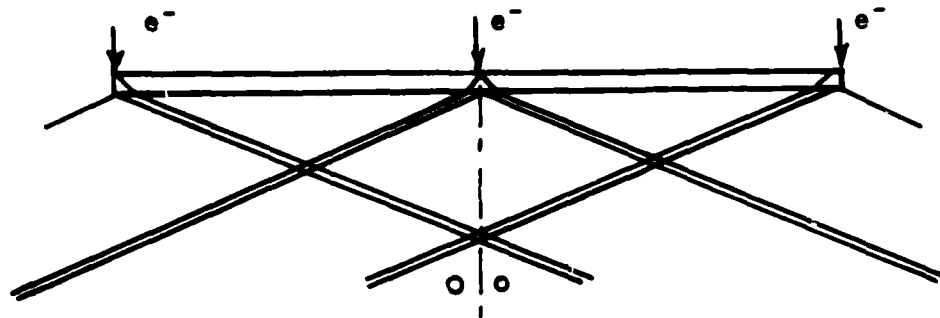


Figure 3. A horizontal plane, through the pilot's eyes and perpendicular to the windscreen, showing the path of light formed by two extreme electrons and one central electron.

The area of the windscreen contributing light to the pupil of one eye is shown in Figure 5. Only the upper half of the windscreen is shown, because the pattern is symmetrical about the horizontal midline. The arcs are formed by two circles, with radii of 62.4 cm and 65 cm inscribed about the intersection of the right eye line-of-sight and the windscreen. Assuming an average interpupillary distance of 65 mm, the projection of the center of the right entrance pupil is 3.25 cm from the vertical midline. The angular extent of the arcs is shown; and the total length of all four arcs is 60.8 cm, which, with the 2.63 width of the arcs, gives an area of 160 cm<sup>2</sup> of the windscreen-containing electrons which contribute to light at the pupil. Hence we can calculate the illumination at the pupils for an electron beam exposure. One rad will provide  $1.6 \times 10^9 e^-$  on the area. From Eqs. 9 and 10, the illumination at the pupil of each eye, from the windscreen, will be:

$$E_w = 2.5 \times 10^{-7} \text{ scotopic lm}\cdot\text{sec}/\text{cm}^2, \text{ and} \quad (13)$$

$$E_w = 7.7 \times 10^{-8} \text{ photopic lm}\cdot\text{sec}/\text{cm}^2. \quad (14)$$

A similar analysis yields the illumination at the pupils for the visor. The distance from the projection of the center of the pupil on the visor is 10.75 cm from one edge and 4.25 cm from the other edge. Since no light reaches the eye from the shorter side, each eye is illuminated by just one band of the surface (Fig. 6). The arc length on the front surface is 85.3°, or 11 cm. For a 1-cm wide area at the pupil, 11 cm<sup>2</sup> of the front surface will contain the electrons which contribute light to the eye. Each electron will illuminate an area of 0.175 cm<sup>2</sup> at the pupil; from Eqs. 11 and 12, the illumination at the pupil from the visor is:

$$E_v = 2.6 \times 10^{-8} \text{ scotopic lm}\cdot\text{sec}/\text{cm}^2, \text{ and} \quad (15)$$

$$E_v = 8.2 \times 10^{-9} \text{ photopic lm}\cdot\text{sec}/\text{cm}^2. \quad (16)$$

These values refer to one rad of 0.95 c electrons delivered within 1 sec.

The spatial distribution of the light formed in the eye becomes important in evaluating the cone response. The directional selectivity of the cones was first noted by Stiles and Crawford, who found that light entering near the edge of the pupil was visually less effective than light entering the eye in the center of the pupil. Subsequently, the major portion of the effect was found to be due to the angle at which light enters the cone relative to the cone axis. The retinal receptors are aligned with their axes pointing toward the center of the globe. Electrons entering the eye parallel to the optical axis will produce Cerenkov radiation at an angle  $\theta$ , relative to the direction of travel of the electron. For 2-MeV electrons, the angle  $\theta$  is 38° in the aqueous and vitreous. (The conditions are shown in Fig. 7.) Light passing through the center of the globe

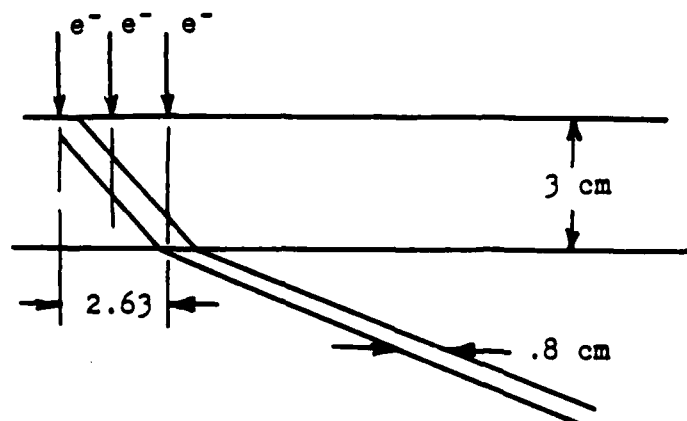


Figure 4. A plane, at 45° to the line through the pilot's eyes and perpendicular to the windscreen, shows a line of electrons which will produce Cerenkov radiation that will reach the pupil of one eye.

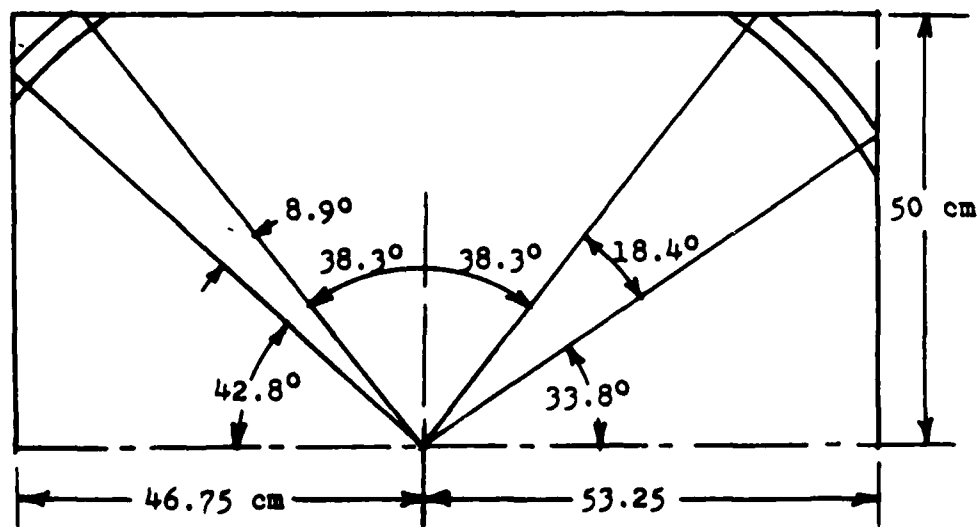


Figure 5. The areas of the windscreen contributing light to the pupil of one eye are shown with their angular extent. Only the upper half is shown because the pattern is symmetrical and is reversed for the other eye.

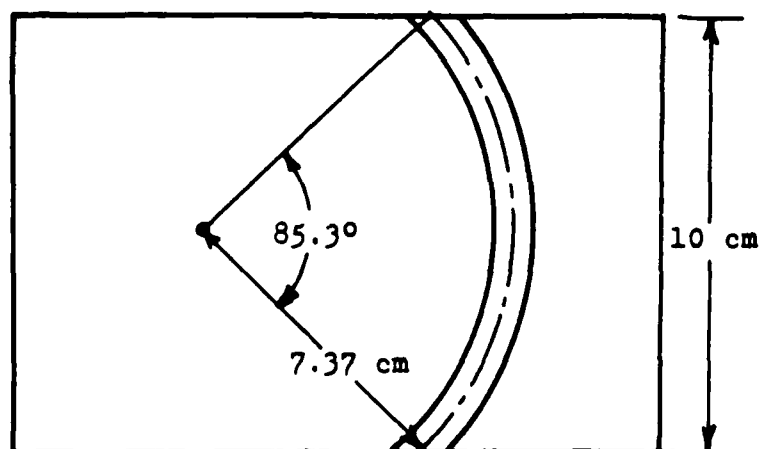


Figure 6. The front surface of the visor, showing the arc that provides illumination at the pupil of the right eye.

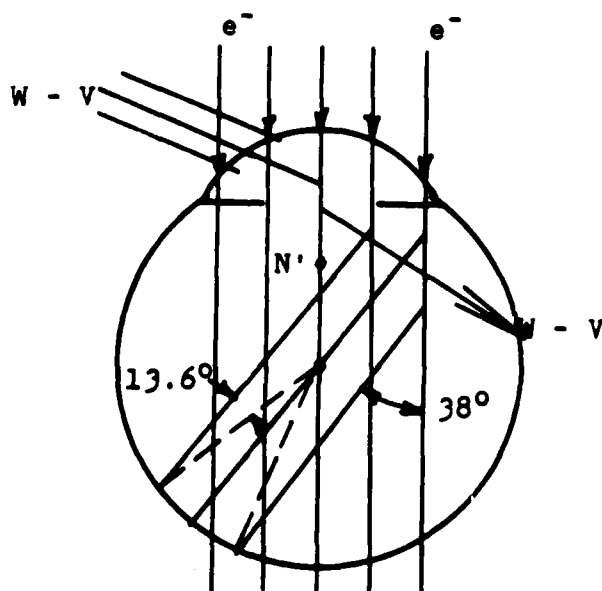


Figure 7. The Cerenkov rays formed in the eye, and the angle they make with the cone axes (dashed lines). The rays marked W-V are light from the windscreen and visor.

will enter a ring of receptors on axis for maximum visual efficiency at an angle of  $38^\circ$  from the optical axis, measured from the center of the globe, corresponding to a visual angle of  $27.9^\circ$ , measured from the nodal point.

Extrapolating the Stiles-Crawford curves for brightness matching, we find a limiting value of  $\pm 13.6^\circ$  to the cone axis. A band of cones around the fovea are stimulated by the Cerenkov radiation. The band extends from a visual angle of  $17.8^\circ$  to  $38.2^\circ$ . The band covers 1.9 sr of the retina, or 1.05 sr of visual angle. As shown in Table 1,  $4.3 \times 10^{-7}$  photopic lm.sec/rad will be received by the area. The integrated Stiles-Crawford curve gives an average effective illumination over the region of 0.31.

### THE RETINAL ILLUMINATION

The unit for expressing retinal illumination, or the number of lumens per unit area, is the troland (td). The basic definition of the troland is the retinal illumination provided by an external source of one candela per square meter, viewed through a pupil area of one square millimeter. The relationship expressed in Eq. 6 can be derived from the definition, and leads to:

$$1 \text{ td} = 3 \times 10^{-10} \text{ lm/deg}^2, \quad (17)$$

where the angular measure refers to visual angle. This is a very useful relationship in comparing unusual light distributions (such as those associated with Cerenkov radiation) with conventional external sources.

The value found in the last section for the visually effective light for cones can be expressed in units of retinal illumination:

$$1 \text{ rad } (0.95 \text{ c e}^-) = 0.127 \text{ photopic td.sec}$$

in a ring of  $17.8^\circ$  to  $38.2^\circ$  visual angles. Cone threshold, when color first appears, is about 0.1 td.sec. Therefore, cone threshold is equivalent to about 0.8 rad, as compared with rod threshold of  $10^{-6}$  rads.

The arcs of the windscreen and of the visor are at a visual angle of  $67.4^\circ$ . The light emerging from the rear surface of the transparencies is in parallel bundles at the pupils and, if optical imagery in the periphery were perfect, they would form line images. The imagery is not perfect, due to off-axis aberrations. More important is the fact that the peripheral receptive fields are very large, thus making nearly impossible any discrimination between a line source and a band of light about  $1^\circ$  in width. If we assume that the light is effectively

smeared to a  $1^\circ$  band, we can calculate the retinal illumination of the regions. The results are listed in Table 2 for mid-scotopic and mid-photopic conditions; the respective light levels correspond to the luminance of a light object of  $5 \times 10^{-4}$  and  $100 \text{ c/m}^2$ . The average pupil areas under these conditions are  $0.45$  and  $0.07 \text{ cm}^2$ . A further correction has been made in the photopic retinal illuminance under mid-scotopic conditions to allow for the Stiles-Crawford effect. The actual pupil area of  $0.45 \text{ cm}^2$  has an effective area of only  $0.24 \text{ cm}^2$  (7).

TABLE 2. THE RETINAL ILLUMINATION FROM CERENKOV RADIATION, PRODUCED BY 1 RAD OF  $0.95 \text{ c}$  ELECTRONS, FOR TWO PUPIL AREAS CHARACTERISTIC OF MID-SCOTOPIC AND MID-PHOTOPIC CONDITIONS

	<u>PHOTOPIC td·sec</u>	<u>SCOTOPIC td·sec</u>
<u>Mid-scotopic 7.5 mm pupil diameter</u>		
Windscreen	1.11	6.74
Visor	0.08	0.45
Eye	0.13	1.74
<u>Mid-photopic 3.0 mm pupil diameter</u>		
Windscreen	0.32	1.05
Visor	0.02	0.07
Eye	0.13	1.74

The two background levels for the calculations give retinal illuminances of  $0.023$  scotopic td and  $0.012$  photopic td for the lower level of  $5 \times 10^{-4} \text{ cd/m}^2$ , and  $700$  td for the higher level of  $100 \text{ cd/m}^2$ . The increment detection thresholds for targets of greater than  $30 \text{ deg}^2$  are available in the extensive work by Blackwell (8) covering various target sizes over a wide range of background luminances. For rod vision, the arcs produced by the windscreen and visor are added to the eye illumination, but the band of light produced in the eye for cone vision does not coincide with the area receiving the external Cerenkov radiation. The beam doses for detection of Cerenkov radiation are listed in Table 3:

TABLE 3. THE DOSE FOR THRESHOLD DETECTION OF THE CERENKOV RADIATION PRODUCED IN THE EYE AND IN THE TRANSPARENCIES FOR TWO LEVELS OF BACKGROUND

<u>DOSE IN RADS</u>			
<u>For Mid-scotopic Level</u>			
<u>Threshold (td·sec)</u>		<u>Windscreen</u>	<u>Eye</u>
Rods	$2.4 \times 10^{-3}$	$2.8 \times 10^{-4}$	$1.4 \times 10^{-3}$
Cones	$2.6 \times 10^{-3}$	$2.3 \times 10^{-3}$	$2.0 \times 10^{-2}$
<u>For Mid-photopic Level</u>			
Rods	2.3	0.27	1.05
Cones	2.3	7.2	17.7

### CERENKOV RADIATION AND FLASHBLINDNESS

As noted earlier, the major amount of work in flashblindness has concentrated on cone vision after intense flashes of greater than  $10^4$  td·sec. Very little has been reported on recovery times of a few seconds for peripheral vision in a subject adapted to scotopic levels of light. Some important information does exist on the early stages of dark adaptation after cessation of steady illumination of fairly low levels. The studies using parafoveal vision usually confine the detection target to about  $5^\circ$  of the fovea instead of the periphery. Two parafoveal studies were done by Bouman (9) and Baker (10), using levels as low as  $10^{-2}$  td. These studies provide some valuable information on the course of dark adaptation, from a few milliseconds to 2 sec.

Baker's results are replotted in Figure 8 in a composite curve. The separate curves for six different experiments, with field luminances from 0.031 to 948 td, were slid along the y-axis to coincide at 0.225 sec; and the data were averaged for each time interval. The solid line in Figure 3 is drawn through the averages, and the vertical lines indicate the range of values at each point. No consistent pattern was noted in the departures from the average as a function of field luminance. The data are for parafoveal detection of a small, brief test flash. The open circles are data for foveal detection for two low values of field luminance, and the recovery is similar to that of the parafoveal data. The absolute threshold for his test flash was  $-1.1 \log \text{td}$ ; and, for the lowest field luminance of 0.031, the threshold was still 0.5 log units above the absolute at 2 sec.

Work that was more directly relevant to the current problem was reported by Crawford (11), and by Boynton and his associates (12, 13). In these studies, a flash (called a conditioning flash) was presented to a subject adapted to a low luminance

field. The foveal thresholds were then measured at short time intervals (20 to 100 msec) before, during, and after the flash. Typical results are shown in Figure 9, in which the log threshold of the measuring flash is plotted against time in seconds from the onset of the flash. In the example shown, the duration of the conditioning flash was 0.6 sec, and the preadapting luminance was 1.3 mL, with the conditioning luminance being a thousand times higher. Two significant points are evident: The sharp rise at the onset and cessation of the flash, and the "anticipatory" rise before the onset. Comparison of Baker's results (Fig. 8), with the portion of the lower curve past 0.625 sec, shows a much steeper decline in the threshold after a flash than after the steady field. The data for Figure 9 were obtained with natural pupils and a  $20^\circ \times 30^\circ$  conditioning field. Fluctuations of the pupil might account for some of the variance, except for the fact that Crawford (11) obtained almost identical results by using artificial pupils.

Unfortunately for the current investigation, none of the well-controlled studies have considered flash intensities in our range of interest or recovery in the far periphery. The lowest field intensity reported was 750 td for 0.524 sec, and the measuring flash was viewed foveally. The highest level of Cerenkov radiation from 10 rads is 85 td-sec for 2-MeV  $e^-$ , and 220 td-sec for 6 MeV. Therefore, our conditions are close to the existing data in intensity. One of the important points demonstrated in the earlier studies is that interrupting a steadily illuminated field measures something quite different from flash effects. The interruption in a steady state of adaptation gives valuable information about the early states of dark adaptation, because the measurements are not contaminated by the onset of light. However, practical problems, requiring a knowledge of recovery times for specific flash conditions, are concerned with the total on- and off-effects of the light and the time interval between them. In all of the flash conditions we have studied, the recovery curve eventually reaches a rate of decline similar to Baker's results; and, at that point, the flash effects due to the onset of the light can be assumed to have ended.

The effects from any conditioning flash can be considered to have three distinct phases: (1) the on-effect, characterized by the sudden increase in threshold to a peak within a few milliseconds of the onset of the flash; (b) the rapid drop from the peak and a slow decline in threshold for the duration of the flash to a few milliseconds before the cessation; and (c) the off-effect, characterized by a rapid drop in threshold and a slower rate of decline as the preadaptation threshold is reached. To assist in predictions, certain generalizations can be drawn from the various studies about each of these phases. It is helpful to define some relationships in terms of the threshold for the measuring flash against steady-state conditions corresponding to the preadaptation level and the conditioning flash level. In this manner, the rise and subsequent drop in threshold during the dynamic events can be expressed without

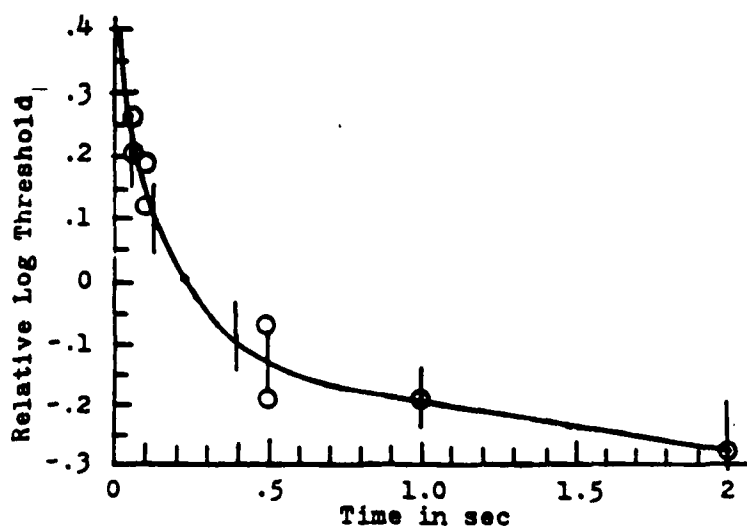


Figure 8. A composite curve of the course of dark adaptation following preadaptation to various light levels from 984 to 0.031 td.

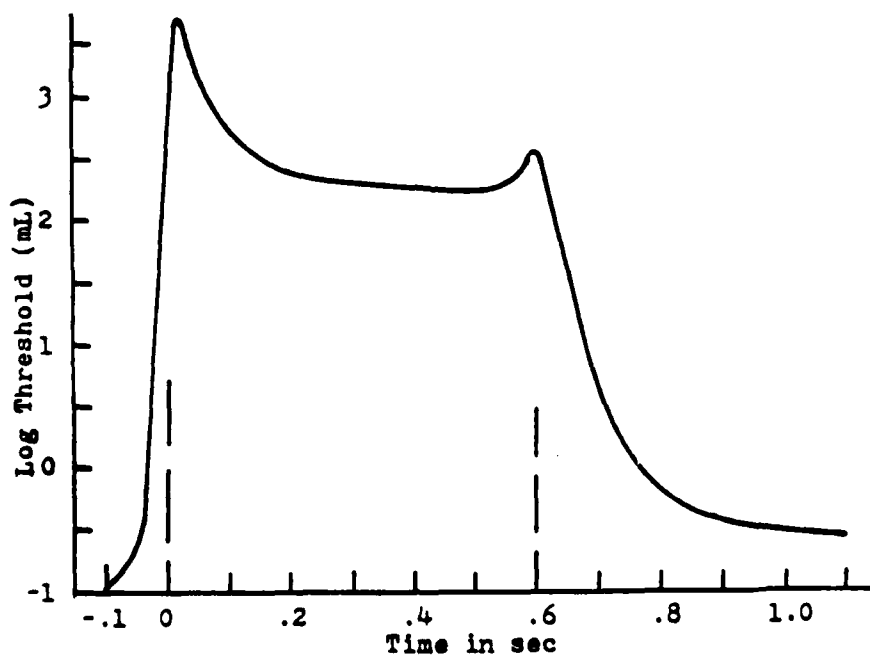


Figure 9. The instantaneous threshold at various times before, during, and after a 0.6-sec flash of 1.1 L.

considering the size or duration of the measuring flash. Another parameter that can be generalized is the ratio of conditioning flash luminance to the preadaptation luminance ( $\log B_2/B_1$ ).

Crawford showed that a 10 times increase in conditioning flash intensity resulted in a 1.3 log unit increase in the peak threshold at the onset of the conditioning flash (11). In this case, the preadaptation level remained constant, so both the intensity and  $\log B_2/B_1$  were varied. Boynton and Miller kept the flash intensity constant, and varied the preadapting luminance to change the ratio (13). The peak threshold, relative to the preadaptation threshold, changed by 1 log unit for a 1 log unit change in  $\log B_2/B_1$ . Thus, both the absolute value of the flash intensity and its ratio to the background are important parameters in describing the onset phase of the flash effects. On this basis, for the 1.3 log unit change in peak threshold found by Crawford (11), only 0.3 log unit is due to the actual increase in flash intensity, and the rest is due to the 10 times increase in the ratio of  $B_2/B_1$ .

The second phase of the flash effects is more easily generalized if the peak threshold is considered an overshoot over the steady-state adaptation threshold for the conditioning field luminance. The overshoot, for a constant value of  $\log B_2/B_1$  equal to 1.5, was 1.6 for a flash luminance of  $1.2 \times 10^3$  mL and 1.1 for 40 mL. The overshoot is expressed as log threshold at peak minus the log threshold for the conditioning luminance. The threshold drops at the rate of 0.6 times the overshoot per 0.1 sec, or until reaching a value of about 0.7 log units. The threshold then declines more slowly to a rate of 0.5 log unit per sec. Therefore, the threshold just prior to the end of the flash can be predicted for durations of 0.2 to 1 sec with some degree of certainty.

The third phase, or the off-effect, is similar in many respects to the second phase. If we consider the threshold at the cessation of the flash as an overshoot as compared with the preadaptation threshold, in a manner analogous to the overshoot of the second phase, the relationships are the same. The initial drop in threshold is at the rate of 0.6 times the "overshoot" per 0.1 sec to a value of 0.7. In this case, the overshoot is defined as the log threshold at the end of the flash minus the steady-state log threshold for the preadaptation level. At the end of the rapid drop, the recovery is similar to Baker's results (10) in Figure 8.

Numerous attempts have been made to describe the underlying physiological basis for the various phases of transient adaptation, but they are beyond the scope of a practical predictive model of specific recovery times. The foregoing description is simply an attempt to isolate the important parameters in order to aid in predicting short-term flashblindness from moderate flashes of about 1-sec duration.

Remember that the description is based on foveal thresholds with fields which are large by laboratory standards, but small as compared with whole eye exposures. If the short-term recovery is due primarily to neural events, a full eye exposure would be expected to have a more profound effect. As noted in many studies, flash effects in the peripheral retina are far stronger than for foveal vision.

Based simply on the foveal data available, a curve similar to that in Figure 9 can be constructed for a 10-rad dose of 2 MeV<sup>-</sup>, with a maximum of 85 td·sec for the mid-scotopic level. The preadaptation threshold for a target of 6° diam or larger is  $2.4 \times 10^{-3}$  td (from Table 3), and the preadaptation level is 0.023 td. Hence the ratio of conditioning flash to preadaptation is 3.6 ( $\log B_2/B_1$ ). The curve in Figure 9 has a ratio of 3.2. The log of the absolute value of the flash is about 4.3, as compared with 1.93 for the Cerenkov flash. A 2.4 log reduction in flash intensity should reduce the peak threshold, and a 0.4-log increase in the ratio should increase the peak above the preadaptation threshold for a value of 4.2 log units. The steady-state threshold for the 85 td·sec Cerenkov flash is -0.06, or 1.6 above the preadaptation threshold; so the overshoot is 2.6. The threshold will reach 0.7 over the Cerenkov threshold at 0.125 sec, and decline to about 0.2 at the end of the flash. At the cessation, the threshold will be 1.85 log units above the preadaptation level, and reach 0.7 units in 1.25 sec. The following decline will result in a threshold twice the preadaptation level at 2 sec following the end of the flash, or a total of a 3-sec interruption in visual detection for targets near threshold.

This example is a seriously oversimplified solution because of the danger in extrapolating from foveal vision to rod vision in the periphery, and in extrapolating below the range of tested values of conditioning field intensities. The example does point up the utility of controlled studies of low-level flashes in the periphery to provide a data base for predictions. No possibility exists for flashblindness from Cerenkov radiation in the mid-photopic range. At best, a retinal illuminance of 10 times the increment threshold could be obtained; and flash effects require several orders of magnitude greater than that for significant recovery periods.

### CONCLUSIONS

The spectral distribution of Cerenkov radiation varies as the inverse third power of the wavelength, so the luminous energy can be solved for any transparent medium for electrons of any velocity above threshold by the relations:

$$Q_v/e^-/\text{cm of path} = 3.9 \times 10^{-14} \sin^2 \theta \text{ photopic lm}\cdot\text{sec, and}$$

$$Q_v/e^-/\text{cm of path} = 1.3 \times 10^{-13} \sin^2 \theta \text{ photopic lm}\cdot\text{sec.}$$

The value of  $\sin^2\theta$  depends on the electron velocity and the index of refraction of the medium. For the conditions selected for this study, the scotopic luminous energy produced in the windscreen was  $2.8 \times 10^3$  greater than in the eye; and the photopic luminous energy,  $3.6 \times 10^3$  greater. The visor with its lower volume produced just 2.3 and 3.6 times that of the eye.

Due to the characteristic directionality of Cerenkov radiation and the refraction away from the normal on leaving the plastic transparencies, only  $1.5 \times 10^{-3}$  of the total luminous energy produced in the windscreen enters the fully dilated pupils of the eyes, and  $1.5 \times 10^{-3}$  of the energy from the visor. Therefore, the visually effective light from the transparencies is 2% of that produced in the eye. The rays of light entering the eye from the external Cerenkov radiation are parallel bundles and, with perfect imagery, would form a line image in the eye. For the flash effects of the radiation to be weighed, these rays can be considered to cover an arc  $1^\circ$  wide at a visual angle of  $67.4^\circ$  from the straightforward line of sight.

To evaluate the flashblindness potential from a 10-rad beam of 0.95 c electrons, a survey was undertaken of the existing data on 1-sec flashes of comparable levels. No pertinent information on recovery times in the periphery was found. Some useful generalizations can be made concerning the flash effects for foveal vision with flash intensities several times greater than the Cerenkov. Any predictions made from the generalizations should be experimentally verified with low-light level flashes of the order of 100 td·sec, and with carefully controlled preadaptation levels in the mid-scotopic range adopted in this study. The threshold should be followed for several seconds, or until it returns to a value 2 to 3 times that of the preadaptation level. Measurements should be made in the periphery at least  $35^\circ$  from the fovea against an extensive background. The importance of the peripheral retina in early warning detection has been amply demonstrated.

The following nine conclusions (a-i) have resulted from this investigation, based on electrons of 0.95 c velocity and a 3-cm windscreen of 1.4 index of refraction at 26 cm from the pilot's eyes. A visor, 0.2 cm thick and of the same index, is 3 cm from the eyes. One rad is equal to a beam density of  $10^7$  e<sup>-</sup>/cm<sup>2</sup>, and the duration is less than 1 sec.

a. The Cerenkov radiation produced in the eye by 1 rad is equivalent to 1.7 scotopic td·sec and 0.127 photopic td·sec.

b. Due to the directional characteristics of cones, the only cones stimulated by the radiation produced in the eye lie in a ring from  $17.8^\circ$  to  $38.2^\circ$  visual angle around the fovea.

c. The absolute rod threshold is 1  $\mu$ rad, and the cone threshold is 0.8 rads.

d. The only portion of the windscreen contributing illumination to the eye lies in four arcs of an annulus, 2.6 cm wide with an inner radius of 62.4 cm, with an area of 160 cm<sup>2</sup>. A total area of 11 cm<sup>2</sup> of the visor contributes to each eye. The areas are seen at a visual angle of 67.4° from the straight-ahead line of sight.

e. For a mid-scotopic level of 0.025 td, the maximum retinal illumination for 1 rad is 8.5 scotopic td·sec from the combined eye and windscreen radiation, and 1.1 photopic td·sec from the windscreen.

f. At the mid-photopic level, the maximum for 1 rad is 2.74 scotopic td·sec, and 0.32 photopic td·sec against the 700-td background.

g. A 10-rad exposure would cause a 2.5-sec interruption in the detection of low contrast targets for rod vision in the mid-scotopic range, based on extrapolations from existing data on foveal thresholds following flashes of less than 1 sec.

h. A lower dose than stated would probably cause a recovery of 2 sec, because of the stronger response of the rod system to flashes; but no pertinent data are available.

i. With sub-lethal doses, no possibility of flashblindness exists in the mid-photopic range.

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